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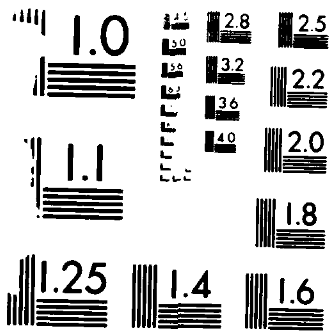


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# REPORT DOCUMENTATION PAGE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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SPECIAL COMMUNICATIONS

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Automated Data Collection and Processing for a Concentric/Eccentric Cycle Ergometer


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Data collection and processing for a cycle ergometer


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## NOTE ON U.S. ARMY HUMAN RESEARCH

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

## ABSTRACT

A system for collection and processing of data from a concentric/eccentric high intensity cycle ergometer is described. Each cycle pedal is fitted with transducers to measure pedal angle relative to the crank and foot forces both perpendicular and parallel to the pedal surface. An additional transducer monitors crank position. Output signals are conditioned, amplified, digitized by a 12 bit A/D converter, fed into a computer at 100 Hz per channel, and mathematically smoothed to attenuate noise. For each sample interval, foot force components perpendicular and parallel to the crank arm are calculated. Power generated by subjects on each crank revolution is determined from transducer information. Computer graphics display pedalling parameters vs. crank angle in both rectangular and circular format. Data files containing variables descriptive of pedalling parameters curves are produced to enable computerized statistical analysis of cycling performance.



mechanical analysis; transducer; computer; force; power

The two most common devices for administration of graded exercise to human subjects in both research and clinical laboratories are the motor-driven treadmill and the leg cycle ergometer. Most of the studies involving cycle ergometers have been directed towards physiological response to quantified power loads, rather than to the mechanics of cycling.

Some mechanical parameters of interest in the study of cycling are angle of the pedal relative to the crank, angle of the crank relative to the cycle, and forces exerted by the foot both perpendicular and parallel to the pedal surface. From these can be calculated force tangential to the arc of pedal travel, torque on the crank shaft, power generated by a subject and measures of efficiency.

Various systems have been devised for measuring force and power developed by a subject on a cycle. Apparatus has included strain gages bonded to the pedal crank (1, 2, 4, 7, 8, 9, 10, 11, 13, 14, 15), and instrumented pedals (3, 4, 5, 12, 16). None of the systems have been able to monitor all of the parameters of interest from both pedals concurrently for a full range of power output up to and including a subject's maximal power. Additionally, none of the systems incorporated an ergometer that could administer quantified loads of eccentric as well as concentric exercise.

Knuttgen et al. (6) have described a leg cycle ergometer that can be set at a wide range of exercise intensities up to and including an individual's maximal power, which for most subjects is far beyond the

power limitations of standard cycle ergometers. Additionally, the ergometer's motor can impose eccentric exercise upon a subject, during which stimulated muscles are stretched.

This article describes a data collection and processing system developed for the high intensity concentric/eccentric cycle ergometer. The system's main design criterion was that it should enable biomechanical analysis of both concentric and eccentric leg cycling exercise through measurement of the mechanical parameters cited above. Though developed for a specific ergometer, the system can be adapted to provide enhanced data collection capability for most commercially available cycle ergometers.

## APPARATUS

### The ergometer

The ergometer for which the data collection system was developed allows positioning of the subject on either a conventional bicycle saddle above the pedal crank or a rigid armchair behind the crank (Fig. 1). The chair is included because with a standard bicycle seat a subject tends to rise as force greater than body weight is exerted on the pedals. Very high forces can be exerted during high intensity cycling, particularly in the eccentric mode. The chair allows the subject to produce large forces without undue body movement, and helps confine the exercise to specific muscle groups. Because of it's advantage for high intensity exercise, the chair was used for the tests whose results are graphically shown below. The distance from

chair to pedal crank is adjustable, and set for each subject so that during cycling, the knee never quite reaches full extension.

During conventional (concentric mode) cycling, the ergometer motor rotates the crank forward at 10% below the RPM setting. A subject must produce power equal to the cycle's watt setting in order to maintain crank rotation at the designated speed. Concentric contractions are performed as the subject's contracting muscles exert force necessary to keep the crank speed up. A metronome, analogue RPM meter, and digital counter inform the subject whether speed is being maintained. For the eccentric mode, the motor rotates the pedals opposite to the normal pedalling direction at 10% above the RPM setting. The subject must absorb power equal to the cycle's watt setting via eccentric contractions, as tense muscles are stretched while exerting force necessary to keep the crank speed down.

Instrumented pedals

Each pedal (Fig. 2), custom designed and manufactured by Sayers Fine Line Design (Clearfield, PA) has a multi-wire electrical connector attached to its outer end providing 5 volts DC excitation to an internal pair of 4-arm temperature compensated strain gage bridges and ±15 volts to a continuous sine wave potentiometer. The strain gage bridges produce voltages corresponding to forces exerted in the pedalling plane by a subject's foot (Fig. 3) perpendicular to the pedal surface (normal force) and parallel to the pedal surface (frictional force), while the potentiometer produces voltage corresponding to the angle of the pedal relative to the crank arm.

Output and input lines both pass through the same pedal connector. The strain gage bridges were tested over a 0-445 N (0-100 lbs) range for normal forces and a 0-1780 N (0-400 lbs) range for frictional forces, showing linearity within 1%. Conformity of the potentiometer output to a sine wave was also within 1%. The potentiometer shaft was adjusted so that the sine wave output corresponding to zero degrees occurs when the pedal surface lines up with the crank arm.

## Crank potentiometer

A continuous potentiometer, linear to within 1%, was mounted behind and attached to the cycle crank shaft by a plastic chain. When provided with ±15 volt DC excitation, the potentiometer produces voltage corresponding to the crank position relative to the cycle body. The potentiometer shaft was adjusted so that it outputs 0.0 volts when the left pedal is at its greatest distance from the exercising subject. When the chair is used, the left crank arm is 15 degrees below horizontal when the crank is at zero degrees.

## Signal processing

In total there are 7 transducer output lines emanating from the cycle, corresponding to: angle of the crank relative to the cycle body; and for each pedal, the frictional force, normal force, and pedal angle relative to the crank arm. Each of the 4 force channels is fed into an interface box, where differential instrumentation amplifiers raise the millivolt output level of the strain gage bridges to the volt range. All 7 channels then pass through Hewlett Packard

preamplifiers which are used to adjust scaling and zeroing and then through a set of isolation amplifiers which reduce noise. Honeywell Accudata amplifiers provide final gain and zero adjustment before the analog signals are digitized by Digital Equipment LPS11 12-bit A/D converters and fed into a PDP 11/40 computer.

## DATA COLLECTION AND PROCESSING

### Computerized data collection

A program was written in FORTRAN for the PDP 11/40 computer to collect data from the cycle ergometer. Two data bases were created to be used in conjunction with data collection. The subject data base contains each subject's name, identification number, sex, date of birth, height, weight, and seat position. The trial-type data base contains different combinations of pedalling direction, mode (concentric or eccentric), and watt setting.

The program includes a calibration procedure. On each data collection day, after the ergometer and signal processing equipment are warmed up, the instrumented pedals are calibrated by placing known weights on them. Specially designed chocks are used to fix the pedals vertically for frictional force calibration, and horizontally for normal force calibration. The program calculates calibration factors necessary to convert values from the A/D converter into meaningful units of force and angle.

When a trial is run, the investigator enters the number of samples to be collected during the trial, the number of pedal revolutions per

sample, and two-digit codes for subject and trial-type. As the subject pedals, a button is pushed which starts data collection when the crank passes 0.0 degrees. Collection stops after the specified number of revolutions. Taking into account the pedal rate setting, the program collects data fast enough to obtain 100 samples per revolution per channel. For example, at 60 RPM the program samples each of the seven channels from the A/D converter at 100 times per second. For a pedal speed of 30 RPM, the program samples at 50 hertz. A trial data file is opened which contains information from both data bases.

The finished data file consists of subject and trial-type information, pedal calibration factors, and a 7 column wide list of numbers representing A/D converter samples from the 7 cycle transducers. The list values are not in meaningful units of force or angle but in "machine units", values from 0 to 4095 represented by the 12 binary bits of the A/D converter, which provide resolution of better than one-fortieth of one percent of full scale. The calibration factors are used to convert machine unit values to newtons and radians. There are 100 rows of transducer data in a file for each cycle revolution sampled. For example, the number of data rows for a trial consisting of three 5-revolution samples is 1500 regardless of the RPM setting.

## Data file processing

The PDP 11/40 computer is reserved for data collection, while processing of the data takes place on a VAX 780. This necessitates transfer of files between the two computers. The transfer is

accomplished by writing the files from the PDP to a magnetic tape, mounting the tape on the VAX tape drive, and recording the file in the VAX memory.

A FORTRAN program was written on the VAX to convert the trial data files into meaningful information. From the file, the program reads subject and trial information, force calibration factors, and the 7-column list of numbers representing the digitized output from the 7 transducer channels. It smooths the data with the ICSSCV cubic spline subroutine from the IMSL library (IMSL; Houston, Texas) which uses statistical considerations to attenuate random noise generated during electronic transduction and processing. Since noise is minimal, little smoothing is required. Calibration factors are used to convert machine units corresponding to normal and frictional forces from each pedal into newtons.

There is no pre-test calibration for either the sine-wave pedal potentiometers or the linear crank potentiometer. Since both the pedals and the crank go through full 360 degree excursions during each cycling revolution, the actual trial data is used to determine calibration factors. Observation of high and low potentiometer output during a pedal revolution along with knowledge of the potentiometer output functions provide enough information for computation of angles from the A/D converter output. A linear potentiometer has the property of producing a signal equal to it's low excitation voltage plus the product of its position as a fraction of full excursion and the difference between the high and low excitation voltages. Conversely, a potentiometer's position can be determined from its output signal.

Since there are $2\pi$ radians in a full crank revolution, angular position is computed from machine unit file values as follows:

$$A_C = 2\pi(M_A-M_L)/(M_H-M_L)$$

where

$A_C$ = crank angle in radians

$M_A$ = machine unit value to be converted to crank angle

$M_L$ = lowest machine unit value during full crank revolution

$M_H$ = highest machine unit value during full crank revolution

A sine wave potentiometer is designed to produce a signal equal to it's low excitation voltage plus the sine of its excursion angle times the voltage range. The zero point on a sine wave is the mean of the high and low points. A sine wave potentiometer's position can be determined from its output by taking the inverse sine of the ratio of the distances from the zero point to the potentiometer reading and from the zero point to the high reading as follows:

$$A_I = \arcsin(M_A-(M_H-M_L)/2)/(M_H-(M_H-M_L)/2)$$

where $A_I$ is an interim angle used for calculation.

The equation simplifies to:

$$A_I = \arcsin((2M_A-M_H-M_L)/(M_H-M_L))$$

Since the arcsin function can only return angles from $-\pi/2$ to $+\pi/2$, calculation of the actual pedal angle $A_P$ from $A_I$ requires consideration of the quadrant in which the angle is located:

| Quadrant | $A_P$ |
|---|---|
| I | $A_I$ |
| II & III | $\pi-A_I$ |
| IV | $2\pi+A_I$ |

The tangential component of foot force on the pedal acts parallel to the pedalling plane and perpendicular to the crank, and importantly, is the only force which directly acts to rotate the crank. The radial component, also parallel to the pedalling plane, is perpendicular to the tangential force. Since radial force acts to stretch or compress the crank arm, but not to rotate the crank, metabolic energy expended to generate radial force may be regarded as a source of inefficiency in pedalling. The tangential and radial components of force on both the left and right pedals are obtained from the normal and frictional forces and the pedal angle relative to

the crank as follows:

$$F_T = \cos(A)\cdot F_N - \sin(A)\cdot F_F$$
$$F_R = \sin(A)\cdot F_N + \cos(A)\cdot F_F$$

where

$F_T$ = sum of tangential force components

$F_R$ = sum of radial force components

$A$ = pedal angle relative to the crank

$F_N$ = normal force on the pedal

$F_F$ = frictional force on the pedal

From the original data file containing 7 columns of information, a new 12 column file is created containing time in seconds, crank angle in radians, and for each side, the pedal angle in radians, and normal, frictional, radial and tangential forces in newtons. Creation of the new, processed files requires considerable computer resources and would take much operator time to process interactively. Instead, large groups of files are submitted on a batch queue for overnight processing. Graphical, statistical, and other secondary programs run much faster using the processed files as input than they would if variable transformations were performed on the original files each time they were to be examined. Interactive operation is facilitated and redundant processing avoided.

Calculation of cycling power

Power is rate of work. Since work is force times distance, and distance along an arc is the product of the arc's radius and subtended angle in radians, work done by the feet on the pedals during a sample interval can be calculated as follows:

$$W = A \cdot R(F_{TL} + F_{TR})$$

where

$W$ = work in joules

$A$ = angle of crank travel in radians

$R$ = distance in meters from crank pivot to pedal

$F_{TL}$ = tangential force in newtons exerted by the left foot

$F_{TR}$ = tangential force in newtons exerted by the right foot

Mean power is calculated by summing the work done during all sample intervals within a time span and dividing by the total number of seconds in the span:

$$P = \sum_{i=1}^{n} W_i \ /(n \cdot t)$$

where

$P$ = power in watts

$i$ = sample interval

$W_i$ = work calculated for the $i^{th}$ interval

$n$ = number of sampling intervals in the time span

$t$ = time span in seconds of the sampling interval

The calculation of power described above is used to evaluate samples of varying numbers of revolutions at less than maximal intensity. In addition, a protocol was designed for determining the maximal power that a subject could generate on the cycle ergometer for one full pedal revolution at a selected pedalling rate.

A max power test is preceded by a brief period of subject warmup. The cycle is then set at a particular revolution speed at which the subject pedals freely. After a countdown, the experimenter pushes the data collection button as the subject begins pedalling with maximal effort. Sampling continues for 5 seconds during which the subject pedals as hard as possible. A computer program processes the data as described above, printing the mean power for each full revolution. Maximal power is taken as the highest mean power generated per revolution.

Computer generated graphics

A FORTRAN graphics program was written using PLOT-10 subroutines (Tektronix, Beaverton, Oregon) to display the variables described above. To provide lucid and varied visual representations of pedalling mechanics, the user is given the following graph parameter choices:

Shape: 1. Rectangular (Fig. 4a)

2. Round (Figs. 4b-4f): The round graph represents a side view of the crank, with the subject pedalling from a seat mounted to the right. Zero degrees on the graph corresponds to the crank position when the subject's left leg is fully extended.

Ordinate: Any of the 12 variables in the processed data file.

Ordinate scaling:

1. Absolute: Scale maximum and minimum set by user(Figs. 4a-4f).
2. Relative: Curves drawn on different scales so that each fills the entire graph. This form is used to compare curve shapes.
3. Auto scaled: Program sets an ordinate window whose minimum is the lowest, and maximum the highest value reached by any of the curves in the graphed set.

Phase compensation:

1. Standard: Curves for both left and right legs displayed as functions of the crank angle, so that they appear 180 degrees out of phase (Figs. 4a & 4b).
2. Phase compensated: Right leg curves shifted by 180 degrees, allowing direct comparison of left and right leg curve shapes (Figs. 4c-4f).

Statistical data file generation

In order to allow statistical comparison of the graphically portrayed curves, a FORTRAN program was written to create variables descriptive of the curve shapes. Using a processed trial data file as input, the program determines the following parameter values and

writes them to a master statistical file:

For the frictional, normal, radial and tangential forces,

a. peak force (N)

b. crank angle at occurrence of peak force (deg)

c. minimum force (N)

d. crank angle at occurrence of minimum force (deg)

e. total impulse per rev (N•sec)

f. positive impulse per rev (N•sec)

g. negative impulse per rev (N•sec)

h. crank angle at beginning of curve ascent (deg)

i. crank angle at end of curve descent (deg)

j. angular range between h. and i. (deg)

k. angular range between h. and b. (deg)

l. angular range between b. and i. (deg)

m. impulse between h. and b. (N•sec)

n. impulse between b. and i. (N•sec)

## DISCUSSION

The data collection and processing system described provides a means for achieving the full research potential of the concentric/eccentric high intensity cycle ergometer. It allows examination of the mechanics of cycling under a wide variety of conditions. More broadly, the system can help to address questions about such topics as concentric vs. eccentric exercise, performance at percent of maximal power, torque-velocity and power-velocity

relationships, bilateral symmetry, the effects of fatigue, feedback training, and efficiency. While designed for and particularly well suited to the concentric/eccentric ergometer, the system could be readily adapted to other cycles. While a standard ergometer might not be able to run eccentrically, or place as great resistive loads on a subject, its usefulness for research could be greatly expanded by a similar computerized data collection system.

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# LEGENDS FOR FIGURES

Fig. 1. Schematic of the concentric/eccentric cycle ergometer.

Fig. 2. Cycle transducers: A) instrumented pedal B) pedal potentiometer C) plastic chain D) crank potentiometer.

Fig. 3. Pedalling parameters:

$F_F$ = frictional force, $F_R$ = radial force,

$F_N$ = normal force, $F_T$ = tangential force,

$A_P$ = pedal angle, $A_C$ = crank angle.

Fig. 4. Pedal forces (N) vs. crank angle (deg.) for a subject pedalling without toeclips at 60 RPM, 485 watts. On circular graphs, inner circle = -500 N, outer circle = 800 N, radii emanate from zero newtons, and * = phase compensated curves.

FIG 1

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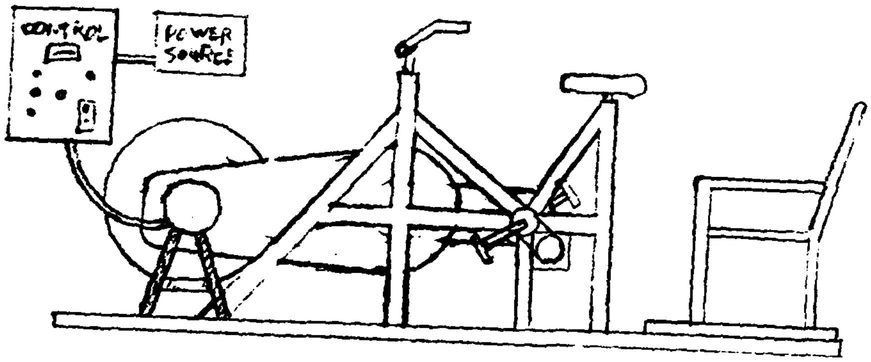
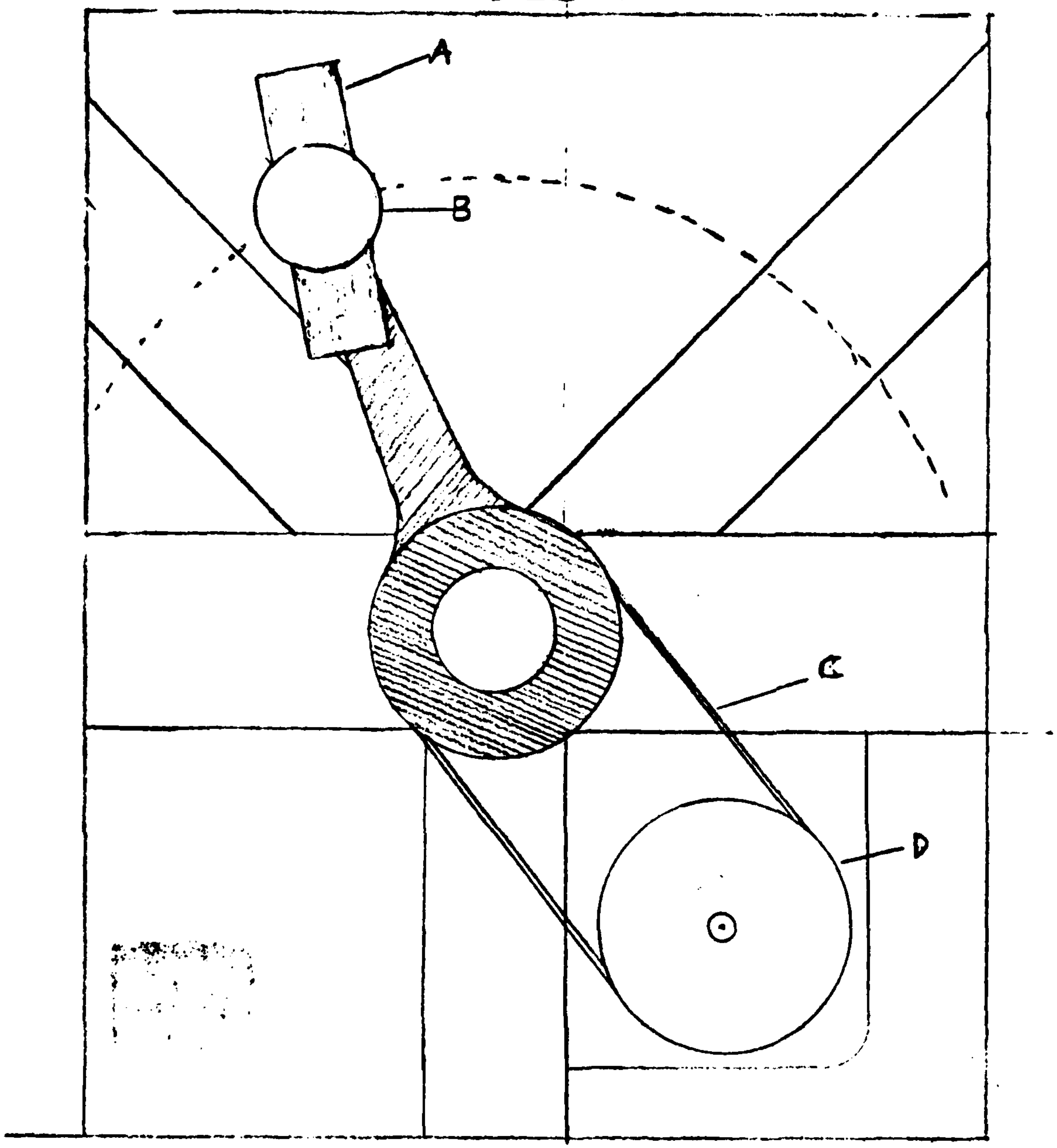



Motor & Flywheel | Gear Exchange | Crank set & pedals | Crank Pot | adjustable seat

TOP




A Instrumented Pedal

B, Pedal angle pot (sin - cosine)

C Toothed belt & gear

D crank angle pot (linear)

- - - - Pedal path

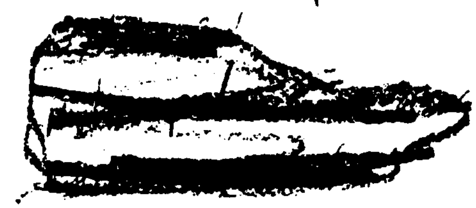


FIG 2

FIG 3

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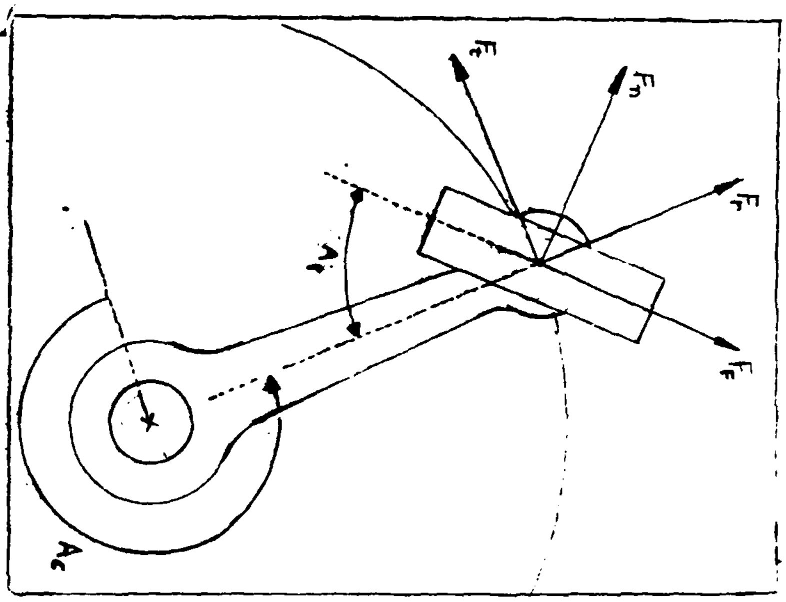
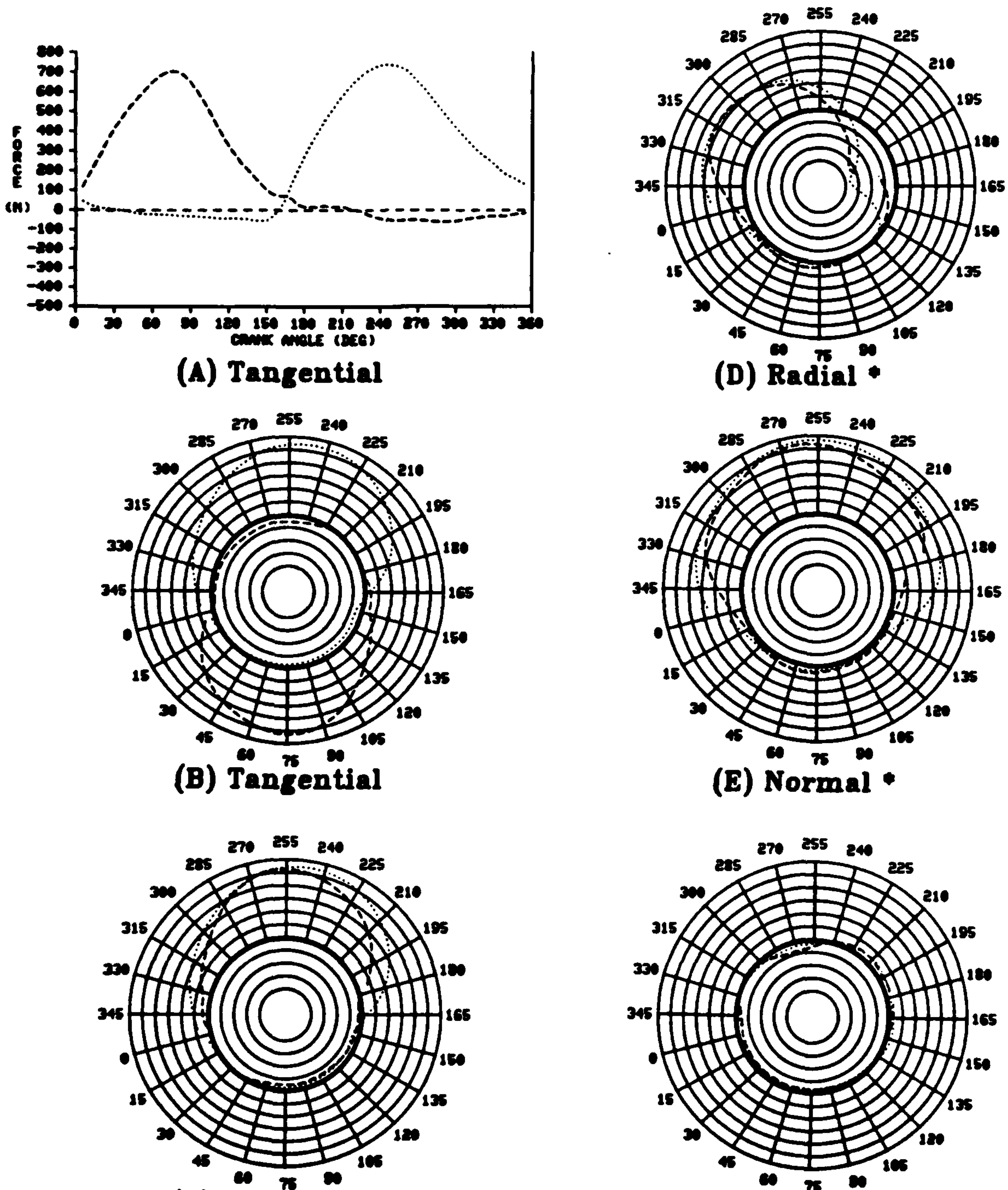


FIG 4

# PEDAL FORCES (N) vs CRANK ANGLE (DEG)

Left Pedal ..........  Outer circle = 800 N

Right Pedal -----  Inner circle = −500 N




(A) Tangential

(D) Radial *

(B) Tangential

(E) Normal *

(C) Tangential *

(F) Friction *

(Radii emanate from zero)  (*=Phase compensated curves)

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